Imaging the End-to-End Dynamics of the Global Solar Wind-Magnetosphere Interaction

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Much of what we know about the solar wind's interaction with the Earth's magnetosphere has been gained from isolated in situ measurements by single or multiple spacecraft. Based on their observations, we know that reconnection, whether on the dayside magnetopause or deep within the Earth's magnetotail, controls the flow of solar wind energy into and through the global system. We know that nightside activity provides the energized particles that power geomagnetic storms. But by their very nature these isolated in situ measurements cannot provide an instantaneous global view of the entire system or its cross-scale dynamics.

As a result, we don't know which mode of reconnection prevails on the dayside magnetopause or within the magnetotail as a function of solar wind and geomagnetic conditions. We don't know which mode or modes of nightside activity supply the most energized particles to the ring current. Nor do we know the dominant loss mode for ring current decay: precipitation, magnetopause outflow, or charge exchange with neutrals. Nor do we know how processes deep within the magnetosphere provide feedback to those happening in the outer magnetosphere. The answers to these questions have an impact far beyond magnetospheric physics, as magnetic reconnection, particle acceleration, and charge-exchange are fundamental plasma processes that operate at other planets and throughout the universe.

Comprehensive end-to-end global imaging of the key micro, meso-, and macro-scale plasma structures that comprise the magnetosphere will provide the answers to these questions via observations with a spatial resolution that exceeds anything possible with in situ measurements. Each proposed interaction mechanism generates a diagnostic plasma structure or boundary signature. Global, end-to-end, imaging provides the pathway to understanding the system as a whole, its constituent parts, and its cross-scale processes on a continuous basis, as needed to quantify the flow of solar wind energy through the global magnetospheric system. The significance of each mechanism is the product of its amplitude and occurrence rate.

This white paper describes how a comprehensively-instrumented single spacecraft in a high-latitude circular polar orbit provides the essential observations needed to track and quantify the flow of solar wind energy through the magnetosphere, including the solar wind plasma and magnetic field input, the magnetopause location in soft X-rays, the auroral oval in far ultraviolet, the ring current in energetic neutrals, the plasmasphere in extreme ultraviolet, the exosphere in Lyman-α, the microstructure of the nightside auroral oval in ground-based all sky cameras, and the magnetic perturbations of ionospheric current patterns seen by ground-based magnetometers.

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Introduction

The overall goal of NASA's Heliophysics program is to understand the Sun and its interactions with the Earth and the solar system. Within this overarching goal, there are three objectives: (1) to understand the nature of our home in space, (2) to solve fundamental mysteries of heliophysics, and (3) to build the knowledge needed to forecast space weather throughout the heliosphere. Because humans and their technological systems, especially spacecraft, are most frequently subjected to space weather effects within the magnetosphere, determining the nature of the solar wind's interaction with the Earth's magnetosphere is central to the Heliophysics program. More than six decades of research have taught us that this interaction is governed by fundamental plasma physics phenomena such as magnetic reconnection, charged particle acceleration, and ion-neutral interactions, that have counterparts throughout the plasma universe. By understanding the nature of these fundamental processes, we can incorporate their physics into state-of-the-art global simulations, improve space weather forecasts within the magnetosphere, and mitigate space weather effects in a timely manner.

Much is known about the solar wind's interaction with the Earth's magnetosphere. Southward IMF turnings enhance the likelihood of magnetic reconnection occurring on the dayside magnetopause. Magnetic flux is opened and removed from the dayside magnetosphere and stored within the Earth's magnetotail for subsequent release via reconnection within the nightside plasma sheet. Magnetic reconnection on the nightside sends streams of particles and powerful field-aligned currents down into the nightside auroral oval and injects both plasma sheet ions and electrons into the Earth's ring current. Nightside reconnection also returns closed magnetic field lines to the dayside magnetosphere, where this sequence of events, known as the Dungey Cycle, can begin anew. This cycle is illustrated in the left-hand panel of Figure 1. ***Over many years, various missions have observed parts of this cycle, but a comprehensive system-level view, from start (at the dayside boundary) to finish (in the inner magnetosphere and ionosphere) is still missing. What is needed is a mission to image the dynamics of the global magnetosphere and its response to solar wind driving.***

Why do we need imaging to solve this problem? First, magnetospheric plasmas are controlled by cross-scale physics; microscale processes can have global consequences. For example, localized magnetopause reconnection reconfigures the global topology of Earth's magnetosphere. Localized and global wave-particle interactions drive rapid changes in the global ring current and radiation belt plasma populations. ranging from near extinction of these plasma populations to order of magnitude enhancements. The significance of these cross-scale phenomena fully justifies the recent emphasis on multipoint missions like Cluster, Van Allen Probes, and MMS; however, these missions could not directly observe the global consequences of the microphysics they studied. ***High fidelity imaging of the magnetosphere's plasma populations provides multi-point observations that quantify the cross-scale physics controlling the dynamics of the system – from global through mesoscale and down to microscale processes.***

A further need for global imaging is the system level nature of the coupled solar wind-magnetosphere interaction; a process atmospheric scientists know as "telecommunication". Processes occurring at isolated locations on the subsolar magnetopause, in the nightside plasma

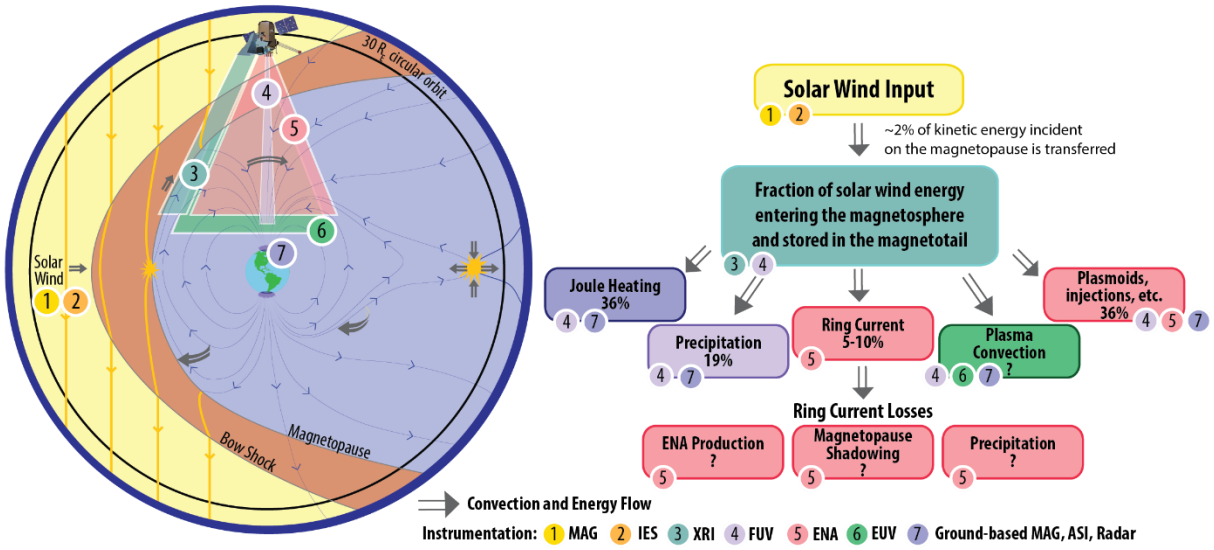

Figure 1: Globally imaging energy flow through the Earth's magnetosphere. Left side shows the fields-of-view and targets for imagers on a single spacecraft in a 30 R_E radius circular polar orbit. Right side relates these imagers to tasks quantifying key components of the global magnetospheric energy budget.

sheet, or deep within the Earth's ring current and plasmasphere can affect the location and nature of dayside reconnection, the cusps, the particle populations precipitating into the auroral oval, or flux levels in the global radiation belt.

Global simulations can help. Both magnetohydrodynamic and hybrid code models have reached the stage where they can make global predictions concerning reconnection, particle acceleration, and ion-neutral interactions occur; however, due to inherent assumptions and missing physics these models can fail to accurately simulate when and where such processes will occur.

Global observations are free from these limitations and therefore provide a complete system science view of the solar wind-magnetosphere interaction. In current budgets a fleet of tens or hundreds of in situ spacecraft is cost-prohibitive. A single global imager provides a cost-effective means of addressing the system science of the magnetosphere with a higher density of observations than any potential in situ mission or fleet of spacecraft, each pixel in an image acting like a virtual in-situ spacecraft. ***Global end-to-end imaging provides a robust and cost-effective method to simultaneously observe the whole system and its constituents to quantify the physics of local and cross-scale processes in the coupled solar wind-magnetosphere system.***

Quantitative Imaging of the Dynamic Solar Wind-Magnetosphere Interaction

System science constitutes in depth studies of the processes occurring within individual regions such as those at the magnetopause, or in the near-Earth magnetotail, ring current, or plasmasphere, as well as studies of their simultaneous interactions as a connected whole. As summarized by Lin et al. (2012) "*when hoping to understand the behaviors of a complex system, one needs to analyze not only how different components work together to form the behaviors of the whole system, but also the behaviors of the individual parts. Without deep and specific comprehension of the behaviors of the individual parts, there will be no way to capture the*

behaviors of the complex system." ***Global imaging determines which of many proposed solar wind-magnetosphere interaction modes dominates as a function of solar wind and geomagnetic conditions, quantifies the fundamental processes controlling these interaction modes, identifies which phenomena must be studied with in situ measurements, and provides the information needed to verify and validate global space weather models. It tracks the end-to-end flow of solar wind energy through the magnetospheric system.***

Let the past estimates for the flow of energy through the magnetosphere, scaled to include loss via plasmoids [e. g., Koskinen and Tanskanen, 2002] shown on the right of Figure 1 serve as a guide to the observational requirements for any comprehensive global imaging mission. Only a small fraction of the solar wind's kinetic energy enters the magnetosphere through the magnetopause. The bulk of the energy that does enter the magnetosphere is stored as open magnetic flux within the Earth's magnetotail, released in the form of field-aligned currents that produce Joule heating of the ionosphere leading to ionospheric outflow, precipitating particles that also heat the ionosphere, and nightside plasma injections that enhance the ring current. Cold plasma from the plasmasphere at the magnetopause may slow dayside reconnection and inhibit the transfer of energy from the solar wind. Ring current loss processes include charge exchange with neutrals, magnetopause outflow, and ring current ion precipitation. Table 1 summarizes the observations needed to identify dominant interaction modes and track energy flow through the magnetosphere.

First, consider the solar wind input. While monitors at the L1 Lagrange point generally suffice to study steady or long-lasting phenomena (geomagnetic storms), they are by no means sufficient to identify or time the arrival of the solar wind discontinuities proposed to trigger individual bursts of reconnection on the magnetopause or nightside substorm onset. For these purposes, near-Earth measurements of the interplanetary magnetic field (IMF) and solar wind plasma, energy input, and triggers are essential.

Next, consider the magnetopause, the boundary controlling the entry of all energy into the coupled solar wind-magnetosphere system. Only a small fraction of the solar wind kinetic energy succeeds in crossing this boundary to power space weather phenomena within the magnetosphere. Observations indicating enhanced magnetospheric activity during intervals of southward IMF orientation demonstrate the importance of magnetic reconnection on the magnetopause to the overall solar wind-magnetosphere interaction. Reconnection erodes the dayside magnetopause, causes the dayside auroral oval to move equatorward, and enables magnetosheath particles to enter the magnetosphere and flow downward to form both the high- and low-altitude cusps. Soft X-ray imagers (XRI) quantify the spatio-temporal dynamics of the magnetopause and high-altitude cusps [Sibeck et al., 2018].

The rate and locations at which the magnetopause erodes inward, the dayside auroral oval moves equatorward, and particles precipitate through the cusps into the polar ionosphere determine the nature of magnetic reconnection on the dayside magnetopause and thus how solar wind energy enters the system. In particular, these parameters quantify the significance of steady and unsteady reconnection modes, patchy and local or global and extended reconnection lines, and identify the locations predicted by e.g., component, antiparallel, or maximum shear models. In conjunction with nightside auroral observations (discussed below) these dayside observations can identify intervals of steady magnetospheric convection in which the

magnetopause location remains nearly stationary because nightside reconnection returns magnetic flux at the same rate as it is being removed by dayside reconnection.

Since magnetic field lines originating in the dayside auroral oval map to locations in the vicinity of the magnetopause, global images of the auroral oval are equally important in determining the processes governing the dayside solar wind-magnetosphere interaction. The variations in open magnetic flux deduced from such images quantify how the dayside oval expands in response to enhanced reconnection, contracts in response to the return of magnetic flux to the dayside from the nightside magnetosphere, or remains stationary during steady-state conditions when flux eroded balances flux returned. Further, the location and temporal variation of the proton aurora define where, when, and how steadily reconnection occurs on the dayside magnetopause. These observations require an imager operating in the Far UltraViolet (FUV).

Magnetopause reconnection consumes magnetic flux and imposes a dawn-to-dusk electric field on the dayside magnetosphere. This electric field causes the plasmapause to move outward, generating plasma plumes that stretch sunward all the way to the locations on the magnetopause where reconnection is occurring. If they reach the magnetopause, they can locally reduce the rate of dayside reconnection. The rate at which plumes move is a direct measure of the electric field applied to the magnetosphere. The dynamics of the plasmasphere, plasmapause, and plumes can be quantified with an Extreme Ultraviolet imager (EUV).

The magnetotail lobes store magnetic flux (and energy) eroded from the dayside magnetosphere. Because the lobes map to the polar cap region enclosed by the auroral oval, the size of the region of open magnetic field lines within the polar cap is a key parameter determining the amount of solar wind energy available for release via nightside magnetic reconnection. As on the dayside, release may come in the form of patchy reconnection that produces a single azimuthally localized bursty bulk flow; a rapid sequence of such bursts that sums to a widespread release; episodic bursts that occur during steady magnetospheric convection events; a single global release; a series of global releases known as sawtooth substorms; or as a sequence of global releases during geomagnetic storms. Whereas global images track the dimensions of the entire auroral oval, ground-based all sky imagers (ASI) provide the high spatial and temporal resolution observations needed to track auroral streamers that correspond in a one-to-one manner to bursty bulk flows within the Earth's magnetotail.

Magnetotail reconnection sends streams of charged particles and field-aligned currents into the nightside ionosphere that cause the aurora to brighten, thereby providing an opportunity for auroral imagers (FUV/ASI) to diagnose the corresponding dimensions and cadences of reconnection in the magnetotail. The extent and time dependence of these brightenings defines the spatiotemporal nature of magnetotail reconnection. The corresponding poleward motions of the nightside auroral oval quantify the magnetic flux closed, the energy transferred, and the significance of individual nightside reconnection modes (FUV/ASI).

Just as dayside reconnection imposes dawn-to-dusk electric fields on the dayside magnetosphere, magnetotail reconnection imposes dawn-to-dusk electric fields on the nightside inner magnetosphere. These electric fields cause the nightside plasmapause to erode earthward. The rate at which the plasmapause erodes is yet another measure of the strength of the electric fields and significance of each proposed individual or sequence of individual nightside interaction mechanisms (EUV).

Table 1: Traceability Matrix for Globally Imaging the Magnetosphere

System Component	Target	Instrument	Comment
Solar Wind Input	IMF	Magnetometer	Cadence sufficient to resolve discontinuity orientation by minimum variance algorithms.
	Plasma	Plasma instrument	Cadence similar to those of imagers
Dayside Reconnection Dynamics	Magnetopause, cusps	Soft X-ray imager (XRI)	Cadence faster than 8-10 min to distinguish steady from bursty reconnection
	Dayside oval, cusps	Far Ultraviolet imager (FUV)	Proton and electron auroral emissions. Cadence similar to that of XRI imager
	Dayside Electric Fields	Extreme Ultraviolet imager (EUV)	Cadence ~minutes sufficient to track plasmapause motion
	Dayside cold/heavy plasma		
Nightside Reconnection Dynamics	Global nightside oval	FUV	Electron auroral emissions, cadence similar to above
	Auroral mesoscale and transients	All Sky Imager (ASI) array	Red, green, blue lines for energy flux. Cadence of ~10s
	Injections	Energetic Neutral Atom camera (ENA)	>3 keV, cadence of 10 min to identify injections
	Nightside Electric Field and plasmasheet sources	EUV	Cadence similar to above
Ring Current Dynamics	Ring current	ENA	>20 keV, cadence similar to above
	Ring current source	ENA, EUV	Cadence similar to above
	Precipitation	FUV	Proton auroral emissions, cadence similar to above
	Magnetopause outflow	XRI	Cadence similar to above
Neutral Density Dynamics	Exosphere	Lyman-α imager	10 min cadences suffice

Magnetotail reconnection injects clouds of ions into the ring current, with penetration depths, spatial extents, and intensities depending on the proposed reconnection mode. Steady or intermittent injections of energized plasma sheet plasma enhance the ion energy stored within the ring current. The rate at which the content of ions within the ring current increases defines the rate of energy transfer to this region of space and the significance of each interaction mode. These dynamics can be observed with an Energetic Neutral Atom camera (ENA).

Three proposed loss mechanisms prevent ring current ion intensities from increasing indefinitely: charge exchange with exospheric neutrals, precipitation into the atmosphere, and magnetospheric outflow through the duskside magnetopause. ENA images diagnose charge exchange, FUV observations of the auroral emissions produced by precipitating protons diagnose loss to the atmosphere, while XRI observations of the dayside magnetopause location and ENA observations of a dawn/dusk asymmetry in ring current ions diagnose loss via magnetopause outflow and shadowing.

One parameter shown in Figure 1 cannot readily be estimated from global imaging missions. Global images cannot quantify all the field-aligned currents that enter the ionosphere and produce Joule heating. However, observations from ground-based radars and magnetometers or low-altitude magnetometers (e. g. AMPERE) can be used for this purpose. The auroral images returned by a global imager provide the magnetospheric context needed to interpret the ionospheric heating rates determined from ground and low-altitude measurements.

Finally, there is value in quantifying the three-dimensional distribution of exospheric neutral densities. Charge exchange of singly-charged hydrogen and oxygen with exospheric neutrals produces the ENA signatures that diagnose the ring current and inner plasma sheet conditions, whereas charge exchange of multiply-charged heavier atoms in the solar wind with exospheric neutrals produces the soft X-ray signals that diagnose the locations of the magnetopause and high-altitude cusps. While the relative importance of the various processes occurring at the magnetopause and in the ring current can be discerned from ENA and soft X-ray observations, information concerning the exospheric neutral densities and ion plasma distributions along their lines-of-sight can be obtained from a Lyman-α imager.

Potential Mission Implementation, Descopes, and Enhancements

With the aid of a single lunar gravitational assist, observations from locations throughout a highly inclined near-circular polar orbit with a radius of 30 R_E are perfectly feasible. As the orbit precesses, the observations described above can be made from all possible vantage points. With a period of ~10 days, this orbit enables continual end-to-end observations of the subsolar magnetopause, the auroral oval, the plasmapause, and the ring current in conjunction with simultaneous observations of the solar wind input through entire phases of geomagnetic storms. This configuration uniquely makes such a mission entirely self-standing, not relying on any other platform to diagnose the system science dynamics of the solar wind-magnetosphere interaction.

As indicated in Table 1 and Figure 1, the payload for such a mission includes in situ observations by a magnetometer and a solar wind plasma instrument, a soft X-ray imager (XRI - the magnetopause), a far ultraviolet imager (FUV - the global auroral oval), an extreme ultraviolet imager (EUV - the plasmapause), an energetic neutral atom imager (ENA - the ring current), and a Lyman-α imager (the exosphere). The mission should be supplemented by an array of all sky imagers (ASI), magnetometers, and radars at high latitudes, of the type already existing across Alaska and Canada, to determine field-aligned currents and Joule heating, as well as to identify the auroral streamers which correspond to mesoscale bursty bulk flows in the magnetotail. No advances beyond existing instrument or spacecraft technology are required for this mission. This mission has been costed and fits well within a MIDEX budget (FY19 $250M).

Possible descopes for the mission include the in-situ measurements, in which case the mission would rely upon observations from one or more monitors at the L1 point or other locations for

solar wind input with reduced accuracy. The Lyman-α instrument could be descoped with the loss of information concerning the absolute densities of the ring current and magnetosheath along the lines-of-sight of the ENA and soft X-ray imagers, respectively. Models for the exosphere, perhaps based upon future observations by the GLIDE mission could be used for this purpose. The extreme ultraviolet imager could be descoped with the loss of information concerning the electric fields impressed upon the magnetosphere, a quantity that could alternatively be determined from measurements by global arrays of ground-based radars.

Should two spacecraft be feasible, tomography and continual observations of the auroral ovals become possible. In this scenario, a moderate-scale mission might comprise two spacecraft separated by 90° (or 10/4 days) along their circular orbits. One of the two polar caps would always be within view of one or the other of the two spacecraft and the orthogonal views of the XRI, ENA, EUV, and Lyman-α imagers would immediately offer the possibility of reconstructing the three-dimensional time-dependent distributions of magnetosheath plasma, ring current ions, plasmaspheric plasma, and exospheric neutral densities. An alternative would be to launch a spacecraft with the X-ray and Lyman-α imagers as well as the in-situ instruments into the 30 R_E circular orbit for global views of the magnetopause and solar wind input, and a spacecraft with the ENA, EUV, and FUV imagers into an elliptical polar orbit with an apogee of 8-10 R_E for close-up high-resolution observations of the ring current and auroral oval, though this separate-launch scenario preclude continuous studies over periods encompassing entire geomagnetic storms. A multiple spacecraft mission will cost between FY19 $350M-$500M depending on the required number of launches and instrumentation.

Transforming Heliophysics with a System-Science Imaging Mission

As described above, a comprehensively instrumented single spacecraft can provide the continuous global images of the magnetosphere needed to distinguish between proposed interaction mechanisms and systematically quantify the importance of each mechanism within the coupled solar wind-magnetosphere system (e. g., determining the occurrence rate and amplitude and thus quantifying the significance of each mechanism). Such a mission provides numerous end-to-end multi-day studies of individual storms supplemented by statistical studies of processes occurring during storm initial, main, and recovery phases. Case studies provide the basis to piece together each component of the system (e. g., dayside reconnection), while statistical studies provide the framework to understand the system as a whole (e.g., system science) as described by Lin et al. [2012]. Precisely these types of observations are needed to verify and validate increasingly sophisticated global simulations of the interaction, and plan the locations, cadences, and observations needed for future constellation missions. The quantitative advancement of knowledge provided by a global imaging mission will be used to first test and then improve space weather forecast models that incorporate its discoveries.

This global imaging mission strongly aligns with Heliophysics objectives. It is the first mission which fully defines the system science of the magnetosphere, specifying the characteristics of the fundamental reconnection, particle acceleration, and ion-neutral and cold plasma interaction processes that underpin this system science. This global end-to-end imaging mission further provides an essential foundation for the Heliophysics System Observatory as well as the observations critical to any magnetospheric or space weather mission or objective.

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